WIND TURBINE CENTRIFUGAL WATER PUMP TESTING

FOR WATERING LIVESTOCK

by

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Summary:

Using a 1.5kW wind turbine as the electrical power source, three centrifugal water pumps were tested with a 1.1kW motor. The lowest stage pump produced the highest water volume and could easily supply enough water for 400 head of cattle at a 30 meter pumping depth (assuming Bushland wind regime).

Keywords:

Wind Turbine, Pumps, Livestock

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ABSTRACT

Using the power generated by a 1.5 kW wind turbine, three different submersible pumps with a 1.1 kW motor were tested at the USDA-ARS Conservation and Production Research Laboratory in Bushland, Texas. The 1.5 kW wind turbine had a rotor diameter of 3.05 meters and generated power with a permanent magnet alternator. The submersible motor and pumps tested could be bought off-the-shelf without any modifications. The submersible motor used in the testing was a 1.1 kW, 230 V, 3-phase motor. The pumps used in the testing were rated at 0.75 kW and differed by the number of stages and flow capacity. The number of stages on the pumps tested were 10, 15, and 19.

The current procedure used for selecting the proper pump for a wind turbine was found to be incorrect. It was also discovered that the maximum flow rate was achieved for the pump with the least number of stages, but the lowest cut-in windspeed was achieved with the pump with the highest number of stages. Future work is discussed which includes testing at deeper pumping depths to determine a better procedure for selecting the proper pump.
KEYWORDS. Wind Turbine, Pumps, Livestock

INTRODUCTION

Testing done at the USDA-ARS Conservation and Production Research Laboratory in Bushland, Texas has investigated the use of wind turbines to pump water for irrigation of crops and watering livestock. Most small wind turbines used for livestock watering use a wind turbine, controller, submersible electric motor, and submersible centrifugal pump. The wind turbine supplies electricity to the electric motor which drives the centrifugal pump. The controller is used to cut-in and cut-out the electricity from the wind turbine to the electric motor when appropriate. The controller is also used to decrease the phase angle between the voltage and current of the wind turbine alternator -- otherwise the electric motor would not run very well. An inverter is not usually used since the inverter will increase the expense and decrease the efficiency of the pumping system. An inverter converts variable frequency and voltage from the wind turbine alternator into constant frequency and voltage.

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For a small pumping head (20 meters) a 1.5 kW wind turbine and a 1.1 kW motor/ 0.75 kW pump was shown to pump twice the amount of water that a mechanical windmill will pump during the year at Bushland, Texas and at about the same cost (Clark and Muhl, 1992). Additional pumping depths (heads) were gathered with this same submersible electric motor and pump (Clark, 1994). The testing reported in this paper involved the same 1.5 kW wind turbine and 1.1 kW motor, but included the testing of two additional 0.75 kW pumps.

Experimental Apparatus

Figure 1 is a drawing which shows how wind energy is used to pump water at the USDA-ARS Laboratory in Bushland, TX. Electricity from the wind turbine or the utility can be supplied to the electric motor by using a double-throw switch. The controller used in this testing had the following functions and settings:

1. Low frequency cut-in (35 Hz.) -- When the electricity reaches 35 Hz from the wind turbine then the electricity is switched to the motor.
2. High frequency cut-out (78 Hz) -- When the electricity reaches 78 Hz from the wind turbine then the electricity is switched off the motor. The wind turbine will become unloaded and the wind turbine rotor will spin faster. The faster spinning rotor results in an increase in the thrust vector on the blades which in turn causes the wind turbine to furl like a conventional mechanical windmill.
3. Low frequency cut-out (25 Hz) -- When the frequency reaches 25 Hz, due to a decrease in wind speed, then the electricity from the wind turbine will be switched from the electric motor.
4. High frequency cut-in (65 Hz) -- When the unloaded wind turbine begins to furl after reaching 78 Hz, the rotor will slow down which means the electrical frequency will decrease until 65 Hz is reached. The electricity from the wind turbine will be switched to the motor. The wind turbine will then begin unfurling.
5. High amp cut-out (8 amps) -- If the frequency doesn't reach the high frequency cut-out before 8 amps is maintained for about 10 seconds, then a circuit breaker will trip and the wind turbine will not come back on-line until the circuit breaker is manually reset.
6. Capacitance included (60 mF/phase) -- Capacitance included to decrease phase angle between voltage and current.

The pressure regulator valve was used to set the pressure in the pumping system to simulate different pumping heads. The back pressure tank was used to steady the pressure in the pumping system. The variables that were measured for all three pumps tested were:

1. Time (Day, Hr., Seconds)
2. Wind turbine hub height wind speed (m/s)
3. Electrical frequency (Hz)
4. Voltage (V)
5. Current (A)
6. Water Pressure (kPa)
7. Flow rate (L/min)

An additional variable wind turbine power (kW) was recorded on the last pump tested. All these variables were sampled each second and the average value was recorded each minute.

Testing

The wind turbine used in the pump testing was a Bergey Windpower[1] 1500. This wind turbine rotor has three fiberglass blades and a 3.05 meter diameter. It protects itself from overspeed by furling horizontally at a windpeed of 13.5 m/s when unloaded. The electricity generated by the permanent magnet alternator is 3-phase variable voltage and frequency. The motor used in the pump testing was a Franklin Electric[1] 1.1 kW, 230 V, 3-phase submersible motor. In other wind electric water pumping experiments a motor which is 1/2 to 3/4's the size of the rating on the wind turbine has always worked best. A major concern of potential buyers of wind electric pumping systems is how long the motor will last. This motor has been tested for almost three years continuously and has not failed. The three pumps used in the testing were a Grunfos[1] 7S10-19, Grunfos 10S10-15, and a Grunfos 16S10-10. The pump model designation used by Grunfos xxSyy-zz means the following:

> xx -- The flow rate that this pump is rated at in gallons/minute.
> yy -- The power in horsepower after being multiplied by 10 (e.g. "10" means 1.0 hp).
> zz -- The number of stages in the pump.

While the 1.1kW motor appears to be optimized for this wind turbine, the optimum pump needed for different pumping depths was not known. Therefore, different pumps were tested to determine the optimum pump for each pumping head. Figure 2 shows the manufacturer's pump curves for the three pumps if the electricity is supplied by the utility. Since the electricity from the wind turbine is variable voltage and frequency, then the pump size selected for the wind turbine is currently being selected according to the following equation

$$\text{Head}_{wind\ turbine} = \text{Head}_{utility}\ (35/60)^2 \tag{1}$$

The 60 in the above equation represents 60 Hz of the utility and 35 represents the cut-in frequency of the wind turbine. Using the above equation then the Grunfos 7S10-19 would be selected for a 50 meter pumping depth, the Grunfos 10S10-15 would be selected for a 40 meter pumping depth, and the Grunfos 16S10-10 would be selected for a 30 meter pumping depth. Therefore, the three pumps were evaluated at 30, 40, and 50 meter pumping depths.

Figure 3 shows the calculated total dynamic head for three different pressure settings when the Grunfos 16S10-10 pump was tested. Similar curves were obtained for the other two pumps. It will be be noticed that the 30, 40, and 50 meter heads were not reached until a wind speed of 12 m/s was reached. Since the pressure settings were set using the electricity from the utility, the wind turbine would act like the utility supplied electricity when this windspeed was reached. In order to determine the measured variables at constant heads of 30, 40, and 50 meters, the variables were linearly interpolated and extrapolated according to the head .vs. windspeed relationship in this figure. The data shown in this figure was completed which meant that at least 1000 minutes of data were collected in each of the 0.5 m/s wind speed bins between 5 and 10 m/s.

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[1]The mention of trade or manufacturer names is made for information only and does not imply an endorsement, recommendation, or exclusion by USDA-Agricultural Research Service

Figure 4 shows the voltage to frequency ratio with respect to wind speed for all three pumps tested and evaluated at a 30 meter head. Similar curves were obtained for heads of 40 and 50 meters. As long as this voltage to frequency ratio is maintained close to 4, then the motor and pump will perform efficiently. The reason "4" is significant is because the motor was designed to operate at 230 volts and 60 Hz (230/60=3.8).

On the last pump tested (Grunfos 10S10-15) power measurements were recorded at each of the three pressure settings. Figure 5 shows the effect of wind speed and pumping depth on the power and power coefficient of the wind turbine. The equation used for the power coefficient was:

$$Cp = P_{wind\ turbine} / P_{wind} = P_{wind\ turbine} / 0.5 * Dens._{air} * Speed^3 * Sref \qquad (2)$$

where $P_{wind\ turbine}$ is the measured power of the wind turbine
             P_{wind} is the power in the wind
             $Dens._{air}$ is the average air density during the testing
             $Speed^3$ is the wind speed cubed
             Sref is the swept area of the wind turbine rotor.

The theoretical maximum for Cp is 16/27(0.593). Because of the low power being measured below a windspeed of 6 m/s then this data is in error. Interestingly the power coefficient is approximately constant between 6 and 12 m/s which is due to the fact that the angle of attack (angle between the relative wind and the blade chordline) is constant. Apparently over this wind speed range the airfoil used on this blade has a constant lift to drag ratio even though the Reynolds Number is changing.

Figure 6 shows the motor/pump efficiency of the Grunfos 10S10-15 pump when evaluated at 30, 40, and 50 meter heads. The equation used for estimating the motor/pump efficiency was:

$$n_{motor/pump} = P_{water} / P_{wind\ turbine} = Dens._{water} * Q * g * H / P_{wind\ turbine} \qquad (3)$$

where P_{water} is the power to lift the water
             $Dens._{water}$ is the density of the water
             Q is the volumetric flow rate
             g is the acceleration due to gravity
             H is the total dynamic head

The time rate of change of kinetic energy was not included in P_{water} because that term is much smaller then the time rate of change of the potential energy. The lowest cut-in wind speed occurred at the lowest pumping depth, but the maximum pump efficiency was achieved with the highest pumping depth.

Figure 7 shows the system efficiency for the three pumps tested when the pumping depth is 30 meters. The equation used for system efficiency was:

$$n_{SYS\ EFF} = P_{water} / P_{wind} = Cp * n_{motor\ pump} \tag{4}$$

Since the system efficiency doesn't require the measurement of power of the wind turbine, then the system efficiency could be calculated for all three pumps. While the data appears to show the lowest cut-in wind speed for the Grunfos 10S10-15 the authors believe the data below 5.5 m/s for this pump is incorrect. Therefore the lowest cut-in windspeed will occur with the pump with the highest number of stages. It will also be noticed that significant improvements in maximum system efficiency were obtained as the number of stages on the pump decreases. The system efficiency results for the different pumps are similar to the pump efficiency results for the different pumping depths.

In order to evaluate which pump is the best at the different pumping depths, the daily water volume has to be determined. In order to determine the daily water volume, the flow rate and hourly distribution of wind speeds has to be determined as a function of windspeed. Figure 8 shows the flow rate as a function of wind speed for all three of the pumps at a pumping depth of 30 meters. For the other pumping depths (40 and 50 meters), the relationship of flow rate to wind speed was the same except the maximum flow rate decreased some and the cut-in wind speeds increased. The same anemometer that was used to measure windspeed in the proceeding analysis was used to produce the wind histogram. Therefore the wind histogram was based on windspeeds that were averaged every minute for one year. The wind speed and air density data used were gathered over one year from April 1, 1993 to March 31, 1994 at Bushland, Texas. Figure 9 shows the average monthly wind speed and air density that was used in the wind histogram. For reference, the sea level standard day air density is 1.225 kg/m³. Since the wind speed is the most important variable for producing wind power due to the cubic relationship, the wind histograms for the highest and lowest average wind speeds in Fig. 9 are shown in Fig. 10. The two wind histograms are very different, and this shows the importance of using actual wind data for predicting water volumes when possible.

Figure 11 shows the predicted volume of water that would be pumped at Bushland over one year (April 1, 1993 to March 31, 1994) for all three pumps tested if the pumping depth was 30 meters. The Grunfos 16S10-10 averages more water per day than the other two pumps at a 30 meter head which was expected. Table 1 shows the average daily water pumped by all three pumps at 30, 40, and 50 meter pumping depths. The Grunfos 16S10-10 averages more water per day than the Grunfos 7S10-19 and 10S10-15 pumps for every month and pumping depth except August and a 50 meter pumping depth. The 10S10-15 pumps slightly more water than the 16S10-10 during this month and pumping depth. These other two pumps (7S10-19 and 10S10-15) would probably pump more water than the 16S10-10 for the same wind histogram at deeper pumping depths.

FUTURE WORK

It now appears that the pump selected for a wind turbine using equation (1) is in error. In order to check this we have planned to simulate deeper well depths with sensors and valves designed to withstand greater pressures. We also intend to test one or more pumps in a 85 meter well at USDA-ARS to check to see if our simulation, which involves linearly interpolating and extrapolating the measured data, is valid.

CONCLUSIONS

The conclusions reached in this paper are:
1. The Grunfos 16S10-10 pump will pump more water than the Grunfos 7S10-19 and 10S10-15 pumps during all months of the year and for pumping depths below 50 meters for a wind regime like that at Bushland, Texas.
2. The current procedure for selecting pump sizes is in error.
3. Additional testing at deeper pumping depths is required to find the proper pump and also help determine a better pump selection procedure.

If the best pump to be used for the Bushland wind regime is one which averages the most water during the month for pumping depths 50 meters and below, then the Grunfos 16S10-10 pump should be selected over the Grunfos 7S10-19 and 10S10-15 pumps. However, another criteria sometimes is to pump at least some water during a string of light wind days which might mean another pump should be selected. This is due to the fact that the pumps with the most number of stages have the lowest cut-in wind speeds. It was also felt that wind-electric pumping systems for heads above 60 meters were not economically feasible if utility electricity was available, but it now appears that view was mistaken.

REFERENCES

1.   Clark, R. N. and Mulh, K. E., Oct., 1992, "Water Pumping for Livestock", Windpower '92 Proceedings, Seattle, Wash., pp. 284-290.

2.   Clark, R. N., May, 1994, "Performance of Small Wind-Electric Systems for Water Pumping, Windpower '94 Proceedings, Minneapolis, Minn., pp. 627-634.

ACKNOWLEDGMENTS

Table 1. PREDICTED AVERAGE DAILY WATER VOLUME PUMPED BY BERGEY 1500.

MONTH	Grunfos 7S10-19 Liters/day(1000)	Grunfos 10S10-15 Liters/day(1000)	Grunfos 16S10-10 Liters/day(1000)	
Apr.	22.9	29.4	36.7	
May	22.6	28.8	35.1	
June	27.7	35.5	46.1	
July	24.7	31.9	39.7	
Aug.	15.4	19.5	21.3	30 METER
Sep.	19.3	24.7	28.9	HEAD
Oct.	16.8	21.4	24.4	
Nov.	20.1	25.7	31.5	
Dec.	19.3	24.7	29.1	
Jan.	16.9	21.8	24.7	
Feb.	21.0	27.0	33.2	
Mar.	21.4	27.3	32.7	
Avg./day	20.7	26.4	31.9	

MONTH	Grunfos 7S10-19 Liters/day(1000)	Grunfos 10S10-15 Liters/day(1000)	Grunfos 16S10-10 Liters/day(1000)	
Apr.	19.3	24.3	28.9	
May	18.7	23.4	27.1	
June	23.6	30.3	36.9	
July	20.8	26.4	31.2	
Aug.	12.3	14.7	15.3	40 METER
Sep.	15.9	19.5	21.7	HEAD
Oct.	13.6	16.4	18.6	
Nov.	16.7	21.0	24.4	
Dec.	15.8	19.5	22.4	
Jan.	13.8	16.8	18.1	
Feb.	17.6	22.1	25.9	
Mar.	17.7	21.9	25.0	
Avg./day	17.1	21.3	24.6	

MONTH	Grunfos 7S10-19 Liters/day(1000)	Grunfos 10S10-15 Liters/day(1000)	Grunfos 16S10-10 Liters/day(1000)	
Apr.	15.9	20.4	23.0	
May	15.3	19.1	21.2	
June	19.7	25.9	29.6	
July	17.2	22.1	24.8	
Aug.	9.6	11.2	11.0	50 METER
Sep.	12.8	15.5	16.5	HEAD
Oct.	10.8	13.1	14.6	
Nov.	13.7	17.3	19.1	
Dec.	12.8	15.8	17.6	
Jan.	11.1	13.1	13.5	
Feb.	14.5	18.4	20.4	
Mar.	14.4	17.9	19.2	
Avg./day	14.0	17.5	19.2	

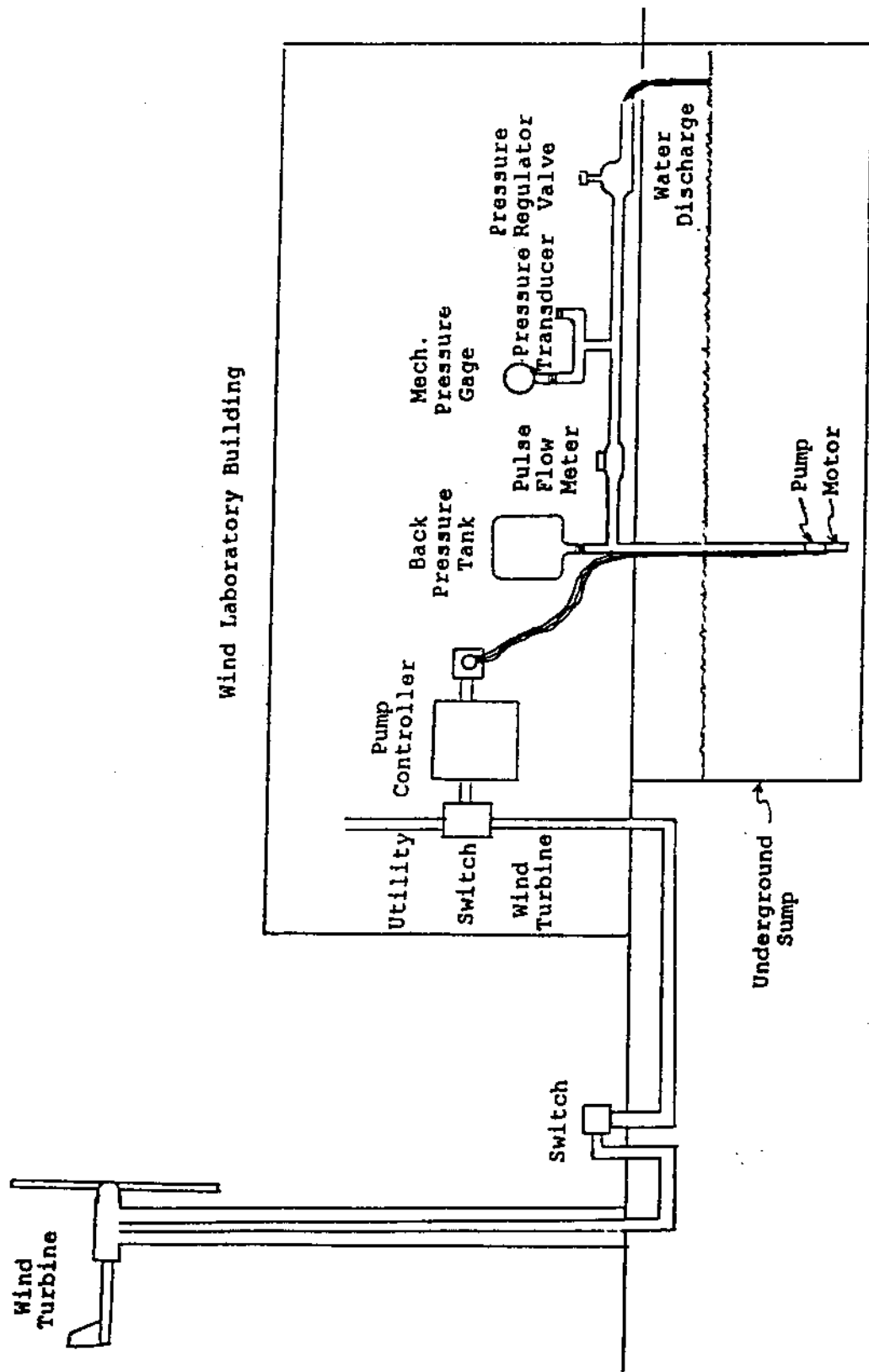*VOLUME BASED ON WIND DATA COLLECTED AT 20 METER HT. IN BUSHLAND, TX

Figure 1. Drawing of Water Pumping Performance Testing at the USDA-ARS, Bushland, Texas
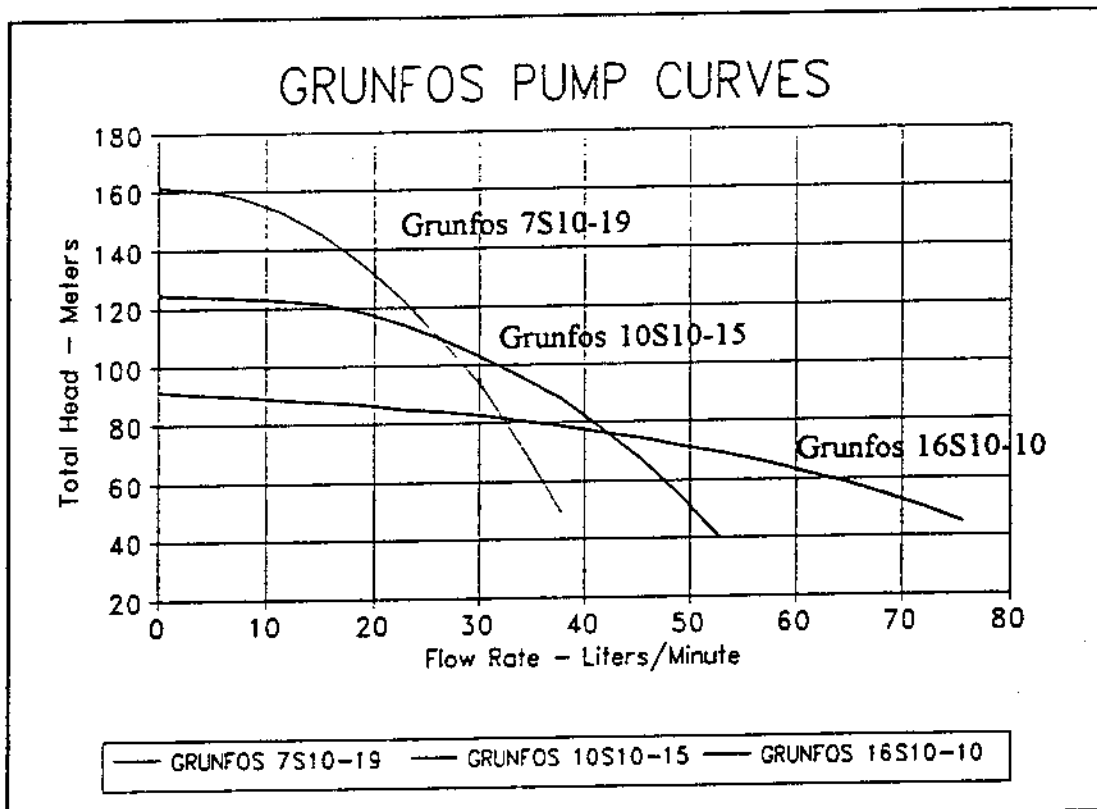
GRUNFOS PUMP CURVES

Grunfos 7S10-19

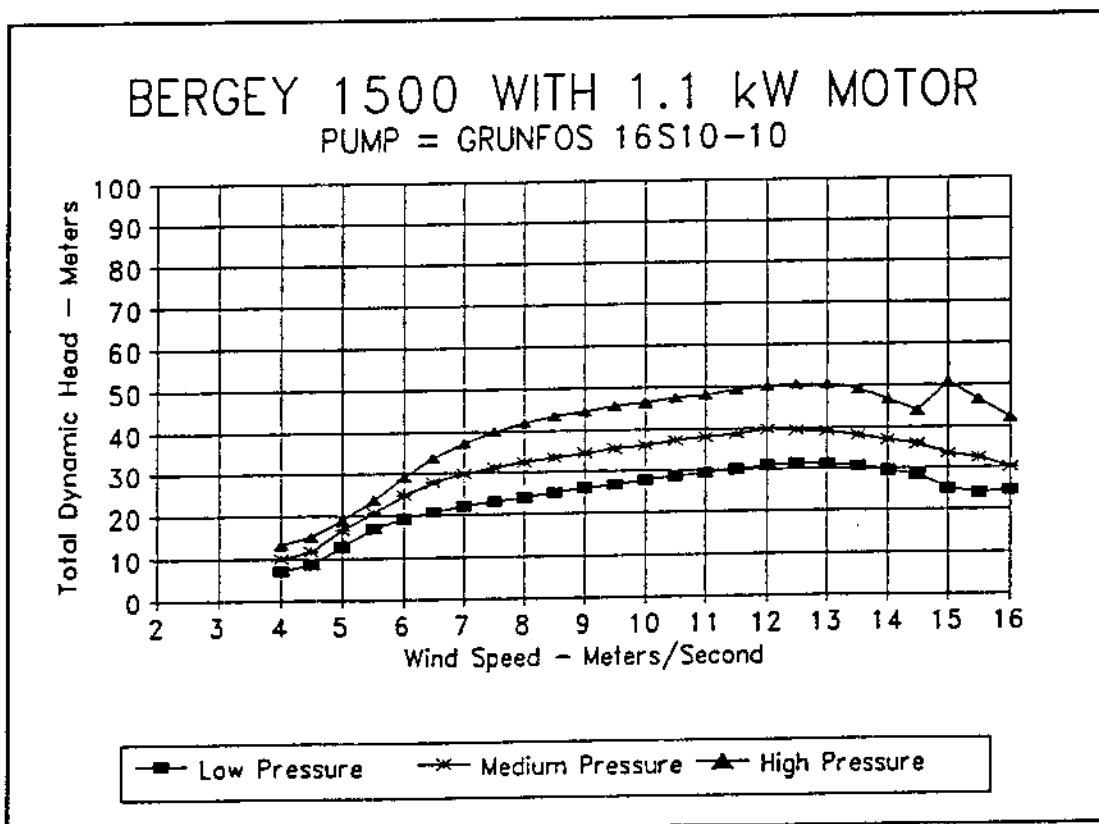Grunfos 10S10-15

Grunfos 16S10-10

Total Head — Meters

Flow Rate — Liters/Minute

GRUNFOS 7S10-19 — GRUNFOS 10S10-15 — GRUNFOS 16S10-10

Figure 2. Grunfos Pump Curves (Manufacturer).

BERGEY 1500 WITH 1.1 kW MOTOR
PUMP = GRUNFOS 16S10-10

Total Dynamic Head — Meters

Wind Speed — Meters/Second

Low Pressure — Medium Pressure — High Pressure

Figure 3. Calculated Total Dynamic Head.

BERGEY 1500 WITH 1.1 kW Motor
HEAD = 30 METERS

Legend: ■ GRUNFOS 7S10-19   ✳ GRUNFOS 10S10-15   ▲ GRUNFOS 7S10-19
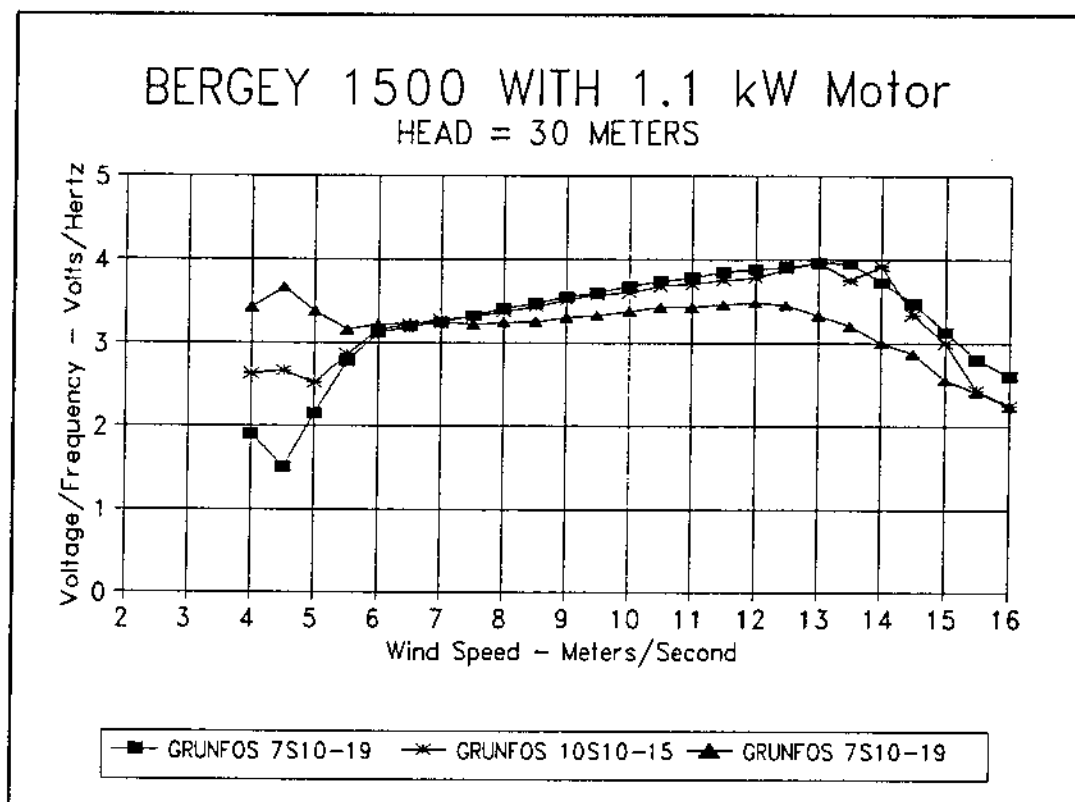
Figure 4. Voltage to Frequency Ratio for Three Pumps.

BERGEY 1500 WITH 1.1 kW MOTOR
PUMP = GRUNFOS 10S10-15

Legend: ■ Power, 30m Head   ✳ Power, 40m Head   ▲ Power, 50m Head
□ Cp, 30m Head   ✕ Cp, 40m Head   + Cp, 50m Head
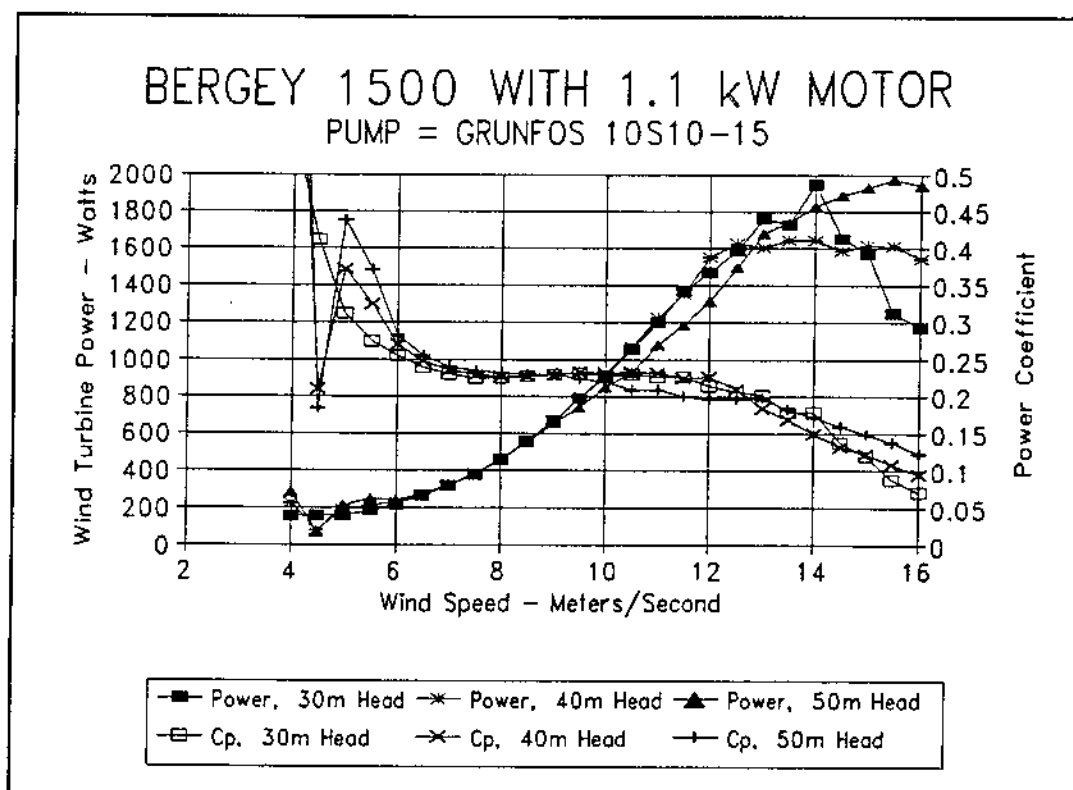
Figure 5. Power and Power Coefficient of Bergey 1500.

BERGEY 1500 WITH 1.1 kW MOTOR
PUMP = GRUNFOS 10S10-15
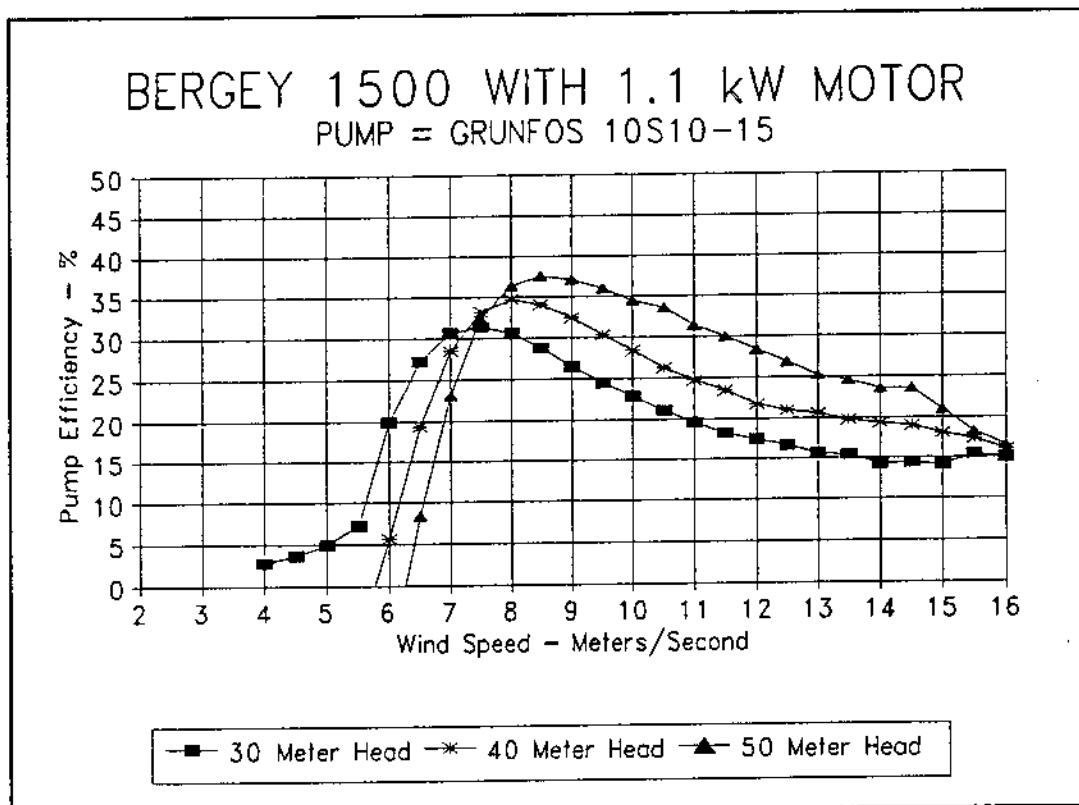
Figure 6. Pump Efficiency for Different Pumping Depths.

BERGEY 1500 WITH 1.1 kW Motor
HEAD = 30 METERS
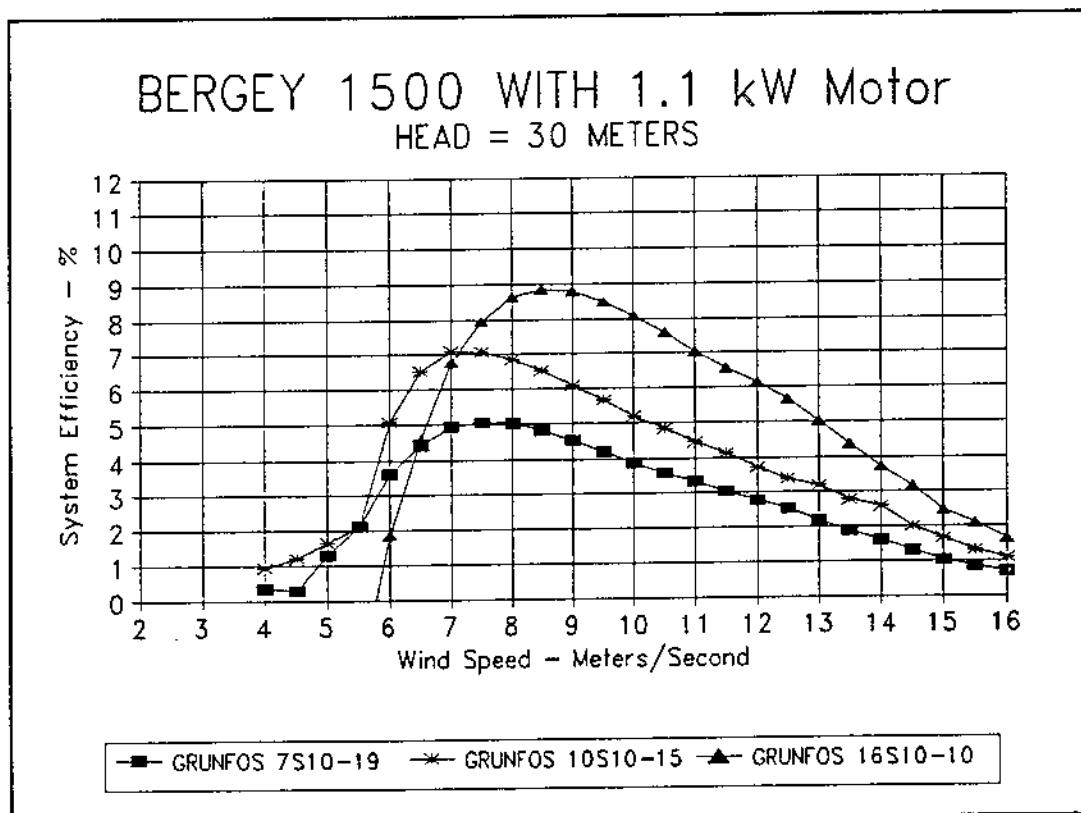
Figure 7. System Efficiency for Different Pumps.

BERGEY 1500 WITH 1.1 kW Motor
HEAD = 30 METERS
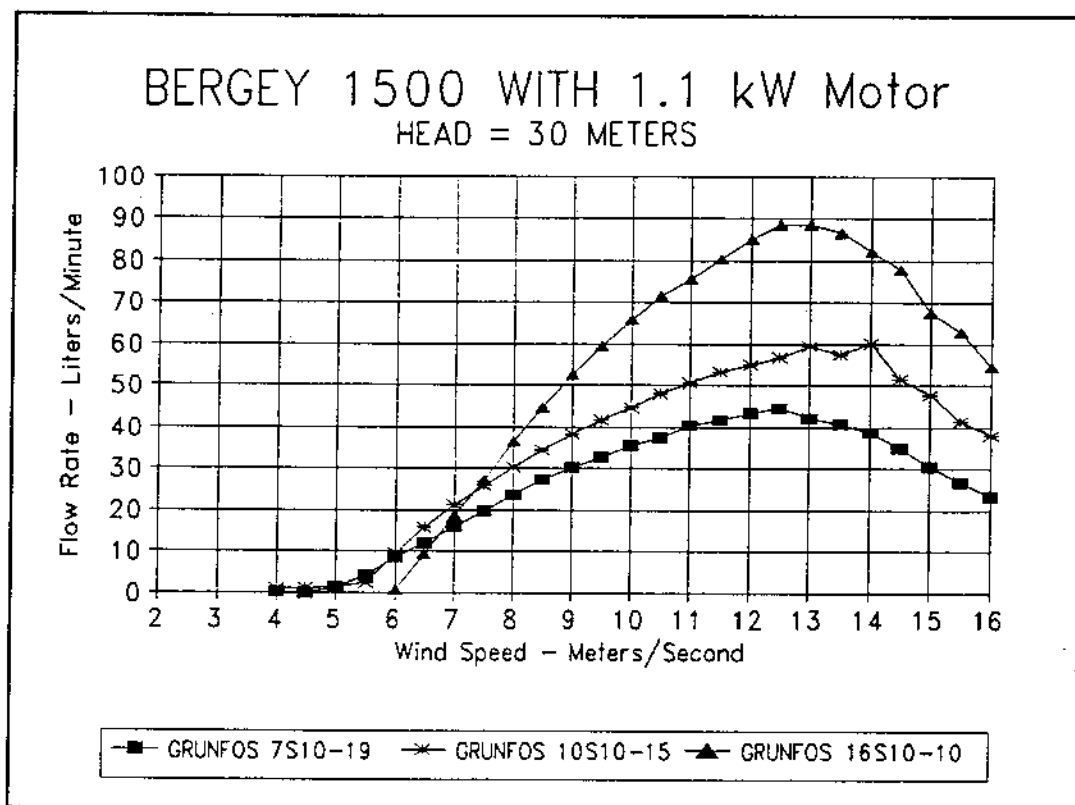
Figure 8. Effect of Pump on Flow Rate.

AVG. MONTHLY WIND SPEED AND AIR DENSITY
WIND SPEED MEASURED AT 20 METERS
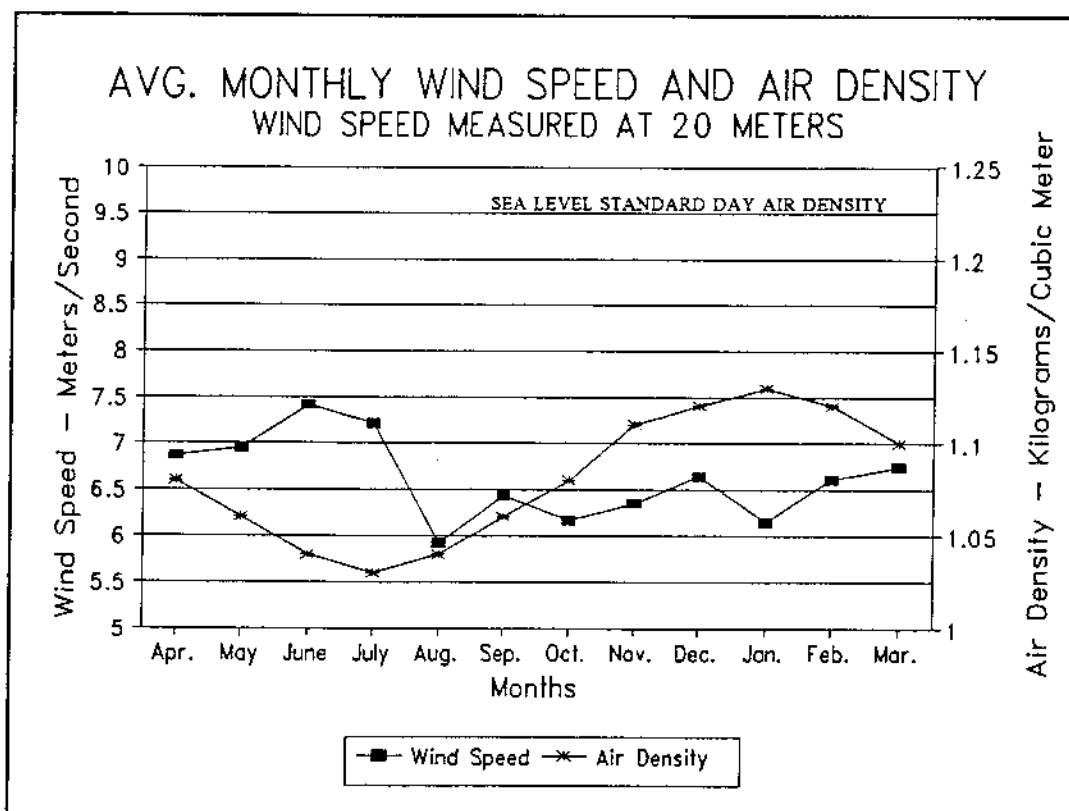
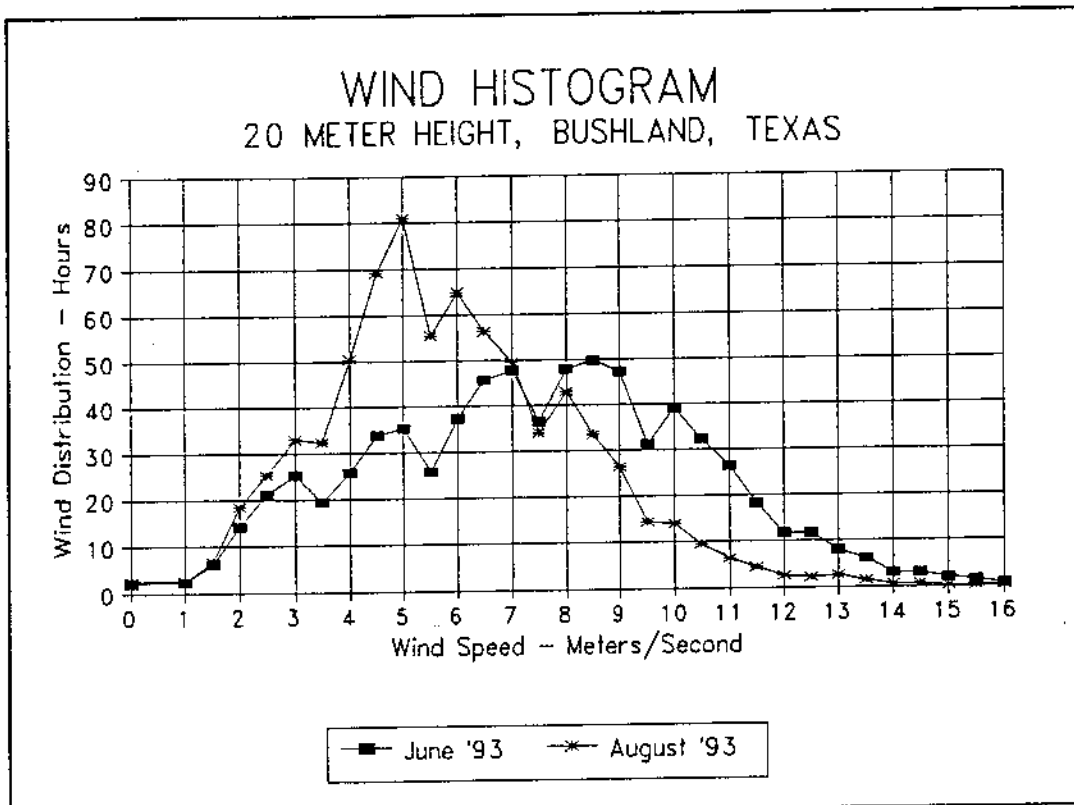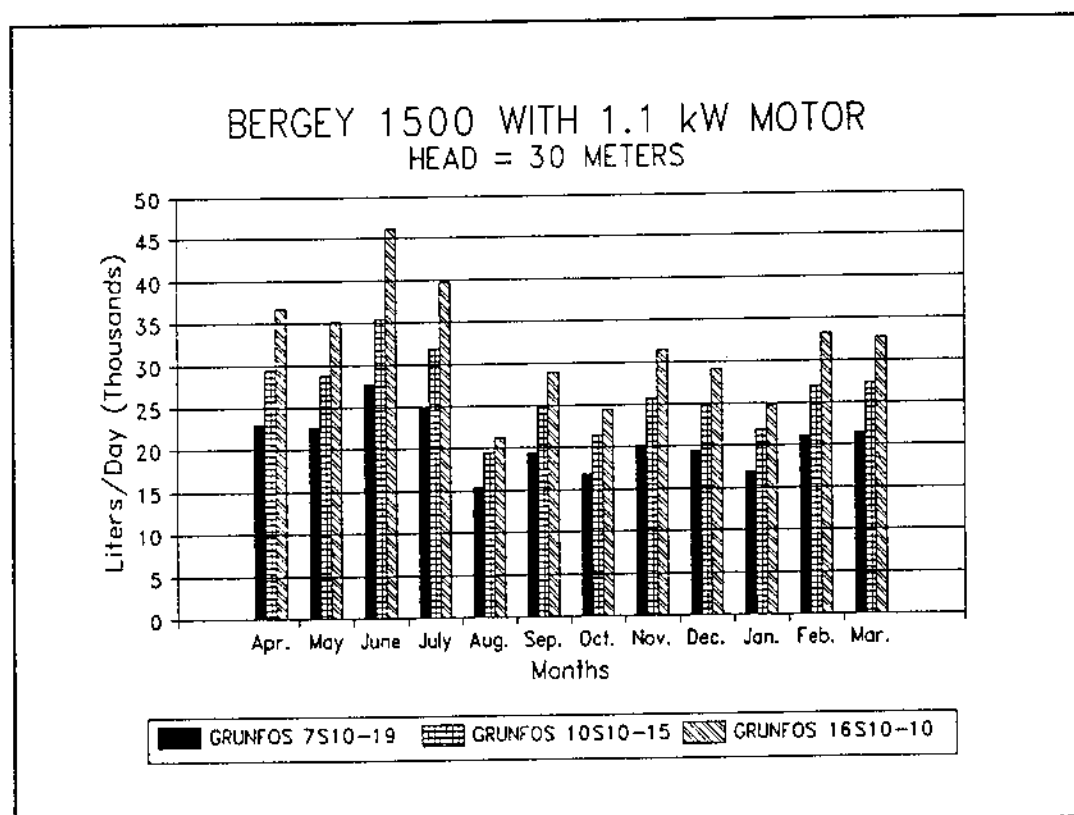Figure 9. Wind Speed and Air Density, Bushland, Tx.

Figure 10. Wind Histogram, Bushland, TX.

Figure 11. Predicted Average Daily Water Volume.